First Results from CLEO-c

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CLEO Collaboration

• CLEO-c Physics Program
• \( D^+ \rightarrow \mu^+ \nu_\mu \) Decays
• Absolute \( Br(D \rightarrow \text{hadrons}) \)
• \( e^+e^- \rightarrow \sigma \) (DD)
• Summary
Heavy Flavor Physics: “overcome QCD roadblock”

- CLEO-c: precision charm absolute Br measurements

  Leptonic decays \(\rightarrow\) decay constants

  Semileptonic decays \(\rightarrow\) V_{cd}, V_{cs}, V_{CKM} unitarity check, form factors

  Absolute D Br’s normalize B physics

  Test QCD techniques in c sector, apply to b sector

  \(\Rightarrow\) improved V_{ub}, V_{cb}, V_{td}, V_{ts}

Physics beyond SM will have nonperturbative sectors

- CLEO-c: precise measurements of quarkonia spectroscopy & decay provide essential data to calibrate theory.

Physics beyond SM: where is it?

- CLEO-c: D-mixing, charm CPV, charm/tau rare decays.
Why Charm Threshold?

- Large production $\sigma$, low decay multiplicity
- Pure initial state (D$\bar{D}$): “no” fragmentation
- Double tag events: “no” background
- Clean neutrino reconstruction
- Quantum coherence:
  - aids D-$\bar{D}$ mixing and CPV studies
<table>
<thead>
<tr>
<th>Year</th>
<th>Energy (GeV)</th>
<th>Luminosity (fb⁻¹)</th>
<th>Events</th>
<th>Tagged Events</th>
<th>Comparison</th>
<th>Decay ( J/\psi ) ( \rightarrow D \bar{D} ) Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>( \psi(3770) )</td>
<td>3</td>
<td>18M DD</td>
<td>3.6M</td>
<td>150 times MARK III</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>( \sqrt{s} \sim 4100 ) MeV</td>
<td>3</td>
<td>1.5M ( D \bar{D}_s )</td>
<td>0.3M</td>
<td>480 times MARK III, 130 times BES</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>( \psi(3100) )</td>
<td>1</td>
<td>1 Billion</td>
<td></td>
<td>170 times MARK III, 15 times BES II</td>
<td></td>
</tr>
</tbody>
</table>
Tagging Technology

Pure DD/D_sD_s production: \( \psi(3770) \rightarrow DD \)
\( \sqrt{s} \sim 4140 \rightarrow D_sD_s \)

Large branching fractions (~1-15%)
High reconstruction efficiency
\Rightarrow High net tagging efficiency ~20%

![Graphs showing M(D) distributions with various cuts and efficiencies.](image1)
![Graphs showing M(D) distributions with various cuts and efficiencies.](image2)
Absolute Br’s w/ Double Tags

~ Zero bkgnd in hadronic modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>PDG2k $(\delta B/B %)$</th>
<th>CLEOc $(\delta B/B %)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^- \pi^+$</td>
<td>3770</td>
<td>2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- \pi^+\pi^+$</td>
<td>3770</td>
<td>7.2</td>
<td>0.7</td>
</tr>
<tr>
<td>$D_s \rightarrow \phi \pi$</td>
<td>4140</td>
<td>25</td>
<td>1.9</td>
</tr>
</tbody>
</table>
\( f_{Dq} \) from Leptonic Decays

\[
\Gamma ( D_q \rightarrow l \nu ) \propto |f_{Dq}|^2 |V_{cq}|^2
\]

w/ 3 fb-1 & 3-gen CKM unitarity:

<table>
<thead>
<tr>
<th>Decay Constant</th>
<th>Reaction</th>
<th>PDG ( \delta f/f )</th>
<th>CLEO-c ( \delta f/f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{D_s} )</td>
<td>( D_s^+ \rightarrow \mu \nu )</td>
<td>12%</td>
<td>1.9%</td>
</tr>
<tr>
<td>( f_{D_s} )</td>
<td>( D_s^+ \rightarrow \tau \nu )</td>
<td>33%</td>
<td>1.6%</td>
</tr>
<tr>
<td>( f_D )</td>
<td>( D^+ \rightarrow \mu \nu )</td>
<td>(~50%)</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
Semileptonic Decays

\[ \text{Br} (D \rightarrow P l \nu) / \tau_D = \Gamma = \gamma |V_{cq}|^2 \]
\[ d\Gamma (D \rightarrow P l \nu) / dq^2 \propto |V_{cq}|^2 |f(q^2)|^2 \]

\[ \delta V_{cd}/V_{cd} \& \delta V_{cs}/V_{cs} \sim 1.6\% \]
\[ \delta V_{cd}/V_{cd} = 5.4\% \text{ (PDG04)} \]
\[ \delta V_{cs}/V_{cs} = 9.3\% \text{ (PDG04)} \]
Probing QCD

- Gluons carry color charge $\Rightarrow$ binding: Glueballs = $|gg>$ and Hybrids = $|qqg>$
- Radiative $\Psi$ decays: ideal glue factory
- CLEO-c: $\sim 10^9 \ J/\Psi$ decays $\Rightarrow \sim 60M \ J/\Psi \rightarrow \gamma X$

Partial Wave Analysis
- Absolute Br’s: $\pi\pi$, $KK$, $pp$, $\eta\eta$, ...
- E.g.: $f_J(2220)$

$\therefore$ CLEO-c: find/debunk $f_J(2220)$
CLEO-c Detector

B=1.0 T

93% of $4\pi$

$\sigma_{E/E} = 2\%$ @1GeV

= 4% @100MeV

83% of $4\pi$

87% Kaon ID with
0.2% $\pi$ fake @0.9GeV

93% of $4\pi$

$\sigma_{p/p} = 0.3\%$ @1GeV

dE/dx: 5.7% $\pi$ @minI

85% of $4\pi$

p>1 GeV

Data Acquisition:
Event size = 25kB
Thruput $\sim 6$MB/s

Trigger: Tracks & Showers Pipelined
Latency = 2.5 $\mu$s
Leptonic Decays: $D^+ \rightarrow \mu^+ \nu_\mu$

$$Br(D_q \rightarrow l\nu) = \frac{G_F^2}{8\pi} \frac{m_{D_q} m_l^2}{m_{D_q}^2} \left(1 - \frac{m_l^2}{m_{D_q}^2}\right) f_{D_q}^2 |V_{cq}|^2 \tau_{D_q}$$

- $f_{D^+}$ provides “iron post of observation” for Lattice QCD
- $f_{D^+}$ useful for checking potential models
- “Calibrated” Lattice QCD ($f_B/f_D$) + $f_D \Rightarrow f_B$
- $f_B$ + B-mixing m’ments $\Rightarrow |V_{td}/V_{ts}|$ precision
Single D± Tag

\[ e^+e^- \rightarrow \Psi(3770) \]

\[ \int L \ dt = 57 \ pb^{-1} @ \sqrt{s} = \Psi(3770) \]

- D tag side: \( D^- \rightarrow K^+\pi^-\pi^-, K^+\pi^-\pi^-\pi^0, K_s\pi^-, K_s\pi^-\pi^-\pi^0, K_s\pi^-\pi^0 \)
  - \( \pi^\pm/K^\pm \) ID: dE/dx + RICH
  - \( \pi^0 \) recon: \( \gamma \) shower shape/location in CsI
  - \( K_s \) recon: \( \pi^\pm \) kinematic fit to displaced vertex

- Signal side:
  - 1 track from event vertex, min_I in CsI
  - “small” (< 250 MeV) neutral \( \Delta E \) in CsI
  - no reconstructed \( K_s \)

- Key analysis variables:
  - \( M_D^2 = E_{\text{beam}}^2 - (\Sigma \vec{p}_i^\perp)^2 \)
  - \( MM^2 = (E_{\text{beam}} - E_{\mu})^2 - (\vec{p} - \vec{p}_{\mu})^2 \)
$M_D$ Distribution v. D Tag

S: $28575 \pm 286$

B: $8765 \pm 784$
\( \sigma(\text{MM}^2) \approx 0.025 \text{ GeV}^2 \)
Leptonic Decays: Signal Region

Check MC $\sigma(\text{MM}^2)$ w/ data: $D^- \rightarrow K_s\pi^-$

∴ Scale MC $\sigma(\text{MM}^2)$ w/ data:

$\sigma = \frac{0.024}{0.021} \times 0.025 = 0.028 \text{ GeV}^2$
Background + Results

Background estimates via MC

• $D^\pm$ Background:

<table>
<thead>
<tr>
<th>Mode</th>
<th># of Events</th>
</tr>
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<tbody>
<tr>
<td>$D^+ \rightarrow \pi^+\pi^0$</td>
<td>$0.31 \pm 0.04$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0\pi^+$</td>
<td>$0.06 \pm 0.05$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \tau^+\nu$</td>
<td>$0.36 \pm 0.08$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^0\mu^+\nu$</td>
<td>negligible</td>
</tr>
</tbody>
</table>

• $D^0\overline{D^0}$ Background: $0.16 \pm 0.16$ events

• $e^+e^- \rightarrow$ continuum: $0.17 \pm 0.17$ events

∴ O’all Bkg: $1.07 \pm 0.25$ events → $1.07 \pm 1.07$ events

$Br(D^+ \rightarrow \mu^+\nu) = \frac{N_{\text{sig}}}{\varepsilon N_{\text{tag}}}$ & $\varepsilon = 69.9\%$ for $D^+ \rightarrow \mu^+\nu$ recon.

$Br(D^+ \rightarrow \mu^+\nu) = (3.5 \pm 1.4 \pm 0.6) \times 10^{-4}$

$f_{D^+} = (201 \pm 41 \pm 17)$ MeV

Preliminary
Br(D) & \( \sigma(DD) \) M’ment @ \( \sqrt{s} = \Psi(3770) \)

\[
S = 2N_{DD} B \varepsilon_1
\]

\[
D = N_{DD} B^2 \varepsilon_2
\]

\[
B = \frac{2D \varepsilon_1}{S \varepsilon_2}
\]

\( w/ \varepsilon_2 \approx \varepsilon_1^2: \)

\[
N_{DD} = \frac{S^2}{4D}
\]

\[
\Rightarrow \sigma(DD) = \frac{S^2}{4DL}
\]

\[i.e., B \& \varepsilon \text{ independent}\]
Single and Double Tags

- Determine 5 Br’s and $\sigma(e^+e^- \rightarrow D^0\bar{D}^0)$ & $\sigma(e^+e^- \rightarrow D^+D^-)$
- 10 Single Tag + 13 Double Tag modes
  - $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+ + \text{c.c.}$
  - $D^+ \rightarrow K^-\pi^+\pi^+, K_s\pi^+ + \text{c.c.}$
- Event selection similar to $f_{D^+}$ analysis
- Key analysis variables:
  - $\Delta E = E_{\text{beam}} - \Sigma E_i$
  - $M_{BC} = \sqrt{(E_{\text{beam}}^2 - (\Sigma p_i)^2)}$
Single and Double Tag Yields

- N(single tags) from ML fit to M_BC
- Line shape parameters from MC
- D and D fit together: same signal param’s, indep. bkg.

\[ D^0 \rightarrow K^-\pi^+ \]

\[ D^0 \rightarrow K^-\pi^+ \]

\[ K^+\pi^-\pi^0 \text{ v. } K^-\pi^+\pi^0 \]

\[ \text{Data} \]

\[ \text{MC} \]
Fit Results for Br(D) and $\sigma(DD)$

- $\chi^2$ fit to account for correlations between single/double tags, bkg
- Fit Output: $\text{Br}(D^0 \rightarrow K^{-}\pi^{+})$, $\text{Br}(D^0 \rightarrow K^{-}\pi^{+}\pi^{0})$, $\text{Br}(D^0 \rightarrow K^{-}\pi^{+}\pi^{-}\pi^{+})$
  $\text{Br}(D^+ \rightarrow K^{-}\pi^{+}\pi^{+})$, $\text{Br}(D^+ \rightarrow K_s\pi^{+})$ and $N(D^0\overline{D}^0)$, $N(D^+D^-)$
- Fit Input: S.T. & D.T. yields, $\varepsilon_{\text{tag}}$, $\varepsilon_{\text{bkg}}$ + errors
- $\chi^2/\text{ndof} = 9.0/16$, C.L. = 91.4%

$\text{Br}(D^0 \rightarrow K^{-}\pi^{+}) = 0.039 \pm ? \pm ?$
$\text{Br}(D^0 \rightarrow K^{-}\pi^{+}\pi^{0}) = 0.130 \pm ? \pm ?$
$\text{Br}(D^0 \rightarrow K^{-}\pi^{+}\pi^{-}\pi^{+}) = 0.081 \pm ? \pm ?$
$\text{Br}(D^+ \rightarrow K^{-}\pi^{+}\pi^{+}) = 0.098 \pm ? \pm ?$
$\text{Br}(D^+ \rightarrow K_s\pi^{+}) = 0.016 \pm ? \pm ?$

$N(D^0\overline{D}^0) = 1.98 \times 10^5 \Rightarrow \sigma(D^0D^0) = 3.47 \pm 0.07 \pm 0.15 \text{ nb}$
$N(D^+D^-) = 1.48 \times 10^5 \Rightarrow \sigma(D^+D^-) = 2.50 \pm 0.11 \pm 0.11 \text{ nb}$

$\sigma(DD) = 6.06 \pm 0.13 \pm 0.22 \text{ nb}$
Summary

I need nicer plots for \( \text{Br}(D \to \text{hadrons}) \)
Backup
1.5 T $\rightarrow$ 1.0T

93% of $4\pi$
$\sigma_{p/p} = 0.35\%$ @1GeV
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85% of $4\pi$
p$>1$ GeV
J/Ψ → γ X Inclusive γ - Spectrum

- Inclusive γ -spectrum
  Search for monochromatic γ
  E.g., 24% efficient for f_J(2220)
  ~10^{-4} sensitivity for narrow resonances
- Modern 4π detector
  Suppress hadronic bkgrnd: J/ψ→π^0X
- Huge data set
  Plus γγ and Υ(1S) data

Determine J^{PC} and gluonic content